SeaWiFS Lunar Calibration Geometry Corrections

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For each lunar calibration, the radiances observed by SeaWiFS are integrated over the lunar image images. The time series used to monitor the radiometric stability of the instrument are the integrated radiances for each band, normalized by the integrated radiances of the first calibration. The time series is shown in the figure *SeaWiFS Lunar Calibration Time Series*. The periodic signals in the time series arise from variations in the geometry of the observations from one lunar calibration to the next. In order to track the radiometric stability of the instrument, the measurements must be normalized to a common viewing geometry. Geometry corrections are computed and applied for the Sun–Moon and instrument–Moon distances, the oversampling of the lunar images in the along-track direction, the phase angles of the observations, and the libration angles of the observations. These corrections are discussed in this document.

1. Distance Corrections

The distance corrections normalize the observations to a Sun–Moon distance of one Astronomical Unit and to an instrument–Moon distance of one mean Earth–Moon distance. The corrections have the form:

$$f_1(t) \;=\; \left(\frac{R_{Sun-Moon}(t)}{AU}\right)^2 \left(\frac{R_{Inst-Moon}(t)}{MLD}\right)^2 \qquad (1)$$

where:

$R_{Sun-Moon}$	$\equiv$	Sun–Moon distance
AU	$\equiv$	Astronomical Unit
$R_{Inst-Moon}$	$\equiv$	Instrument–Moon distance
MLD	$\equiv$	mean Earth–Moon distance = 384401 km
t	$\equiv$	time of the observations

The distance corrections are shown in the figure *Distance Corrections*. The calibration time series with the distance corrections applied are shown in the figure *Lunar Calibration Time Series with Distance Corrections*. The distance corrections have removed the large-scale periodic signal from the time series.

2. Oversampling Correction

During lunar calibrations, the spacecraft pitches across the Moon (in the along-track direction) at a slower rate than the scan rate of the instrument, resulting in an oversampled image of the Moon. The oversampling correction compensates for the pitch rate across the Moon. The correction is computed dividing the angular size of the Moon, as seen from the spacecraft, by the angluar size of the Moon in the along-track direction in the lunar image. The correction has the form:

$$f_2(t, \alpha, \gamma) \;=\; \frac{1}{Y_{Moon}(\alpha, \gamma)} \;\arctan\left(\frac{D_{Moon}}{R_{Inst-Moon}(t)}\right) \tag{2}$$

where:

Y_{Moon}	$\equiv$	angular size of the Moon in the lunar image
D_{Moon}	$\equiv$	diameter of the Moon
α	$\equiv$	phase angle
γ	$\equiv$	track angle

The algorithm used to determine the y-size of the Moon in the lunar images is discussed in the document *SeaWiFS Lunar Image Y-Size Algorithm*.

The mean value of the oversampling correction over the SeaWiFS mission is 0.280 ± 0.007. The oversampling correction, as described here, is used when comparing SeaWiFS lunar observations with external observations or models. For monitoring the radiometric stability of SeaWiFS, the concern is variations in the oversampling from calibration to calibration. Consequently, for correcting the SeaWiFS lunar calibration time series, the oversampling correction time series is normalized by the mean oversampling correction. This normalization yields an oversampling correction time series with a mean value of unity. The normalized oversampling correction is shown in the figure *Oversampling Correction*. The change in oversampling correction between the 6th and 7th lunar calibrations is due to a change in the control gains of the spacecraft attitude control system in May of 1998, which caused in a change in the pitch rate of the spacecraft during the lunar calibrations. The calibration time series with the oversampling correction applied are shown in the figure *Lunar Calibration Time Series with Oversampling Correction*. The oversampling correction reduces some of the high-frequency periodic signal in the time series.

3. Phase Angle Corrections

The phase angle corrections normalize the observations to a lunar phase angle of 7°. The corrections are computed from quadratic fits to the the lunar time series (corrected for distance and oversampling) plotted as functions of phase angle over a range of $4° - 11°$. The corrections have the form:

$$f_3(\lambda, \alpha) \;=\; \left(p_0(\lambda) \;+\; p_1(\lambda)\,\alpha \;+\; p_2(\lambda)\,\alpha^2\right) \tag{3}$$

where:

$p_0 \equiv$ constant term of the correction
$p_1 \equiv$ linear term of the correction
$p_2 \equiv$ quadratic term of the correction
$\lambda \equiv$ SeaWiFS band

The correction yields a value of unity at a phase angle of 7°, values of less than unity at smaller phase angles, and values of more than unity at larger phase angles. The computation of the phase angle corrections is discussed in the document *SeaWiFS Lunar Phase Angle Corrections*. The corrections are shown in the figure *Phase Angle Corrections*. The calibration time series with the phase angle correction applied are shown in the figure *Lunar Calibration Time Sereis with Phase Angle Corrections*. The corrections become significant as the phase angles of the calibrations depart from 7°.

4. Intermediate Time Series

The distance corrections, oversampling correction, and phase angle corrections are computed independently of the lunar calibration time series, while further corrections require the fits to the time series. Consequently, an intermediate time series incorporating the corrections that are independent of the lunar data is computed. The first intermediate time series has the form:

$$\frac{S_1(t,\lambda,\alpha,\gamma)}{S_1(0,\lambda,\alpha,\gamma)} = \frac{S_{obs}(t,\lambda,\alpha,\gamma)}{S_{obs}(0,\lambda,\alpha,\gamma)}\, f_1(t)\, f_2(t,\alpha,\gamma)\, f_3(\lambda,\alpha) \tag{4}$$

where:

$S_1 \equiv$ first intermediate, partially-corrected integrated radiances
$S_{obs} \equiv$ observed integrated radiances

As noted above, the intermediate time series is shown in the figures *Lunar Calibration Time Sereis with Phase Angle Corrections*.

5. Libration Corrections

Libration effects are changes in the lunar radiance as seen from the spacecraft due to variation in the side of the Moon that faces the Earth during the lunar observations (the libration of the Moon). The libration effects are computed from linear regressions of the selenographic longitude and latitude of the sub-spacecraft and sub-solar points on the lunar surface against the first intermediate time series. The libration corrections, which are the inverse of the libration effects, have the form:

$$f_4(l_{sc}, b_{sc}, l_{sun}, b_{sun}) = (c_0 + c_1\, l_{sc} + c_2\, b_{sc} + c_3\, l_{sun} + c_4\, b_{sun})^{-1} \tag{5}$$

where:

$c_0 \equiv$ libration correction constant
$c_1 \equiv$ libration longitude correction coefficient
$c_2 \equiv$ libration latitude correction coefficient

$c_3 \equiv$ libration longitude correction coefficient
$c_4 \equiv$ libration latitude correction coefficient
$l_{sc} \equiv$ longitude of the sub-spacecraft point
$b_{sc} \equiv$ latitude of the sub-spacecraft point
$l_{sun} \equiv$ longitude of the sub-solar point
$b_{sun} \equiv$ latitude of the sub-solar point

The computation of the libration corrections is discussed in the document *SeaWiFS Lunar Libration Corrections*. The mean libration effects for SeaWiFS bands 4 and 5, whose inverse is used to correct all eight bands, is shown in the figure *SeaWiFS Lunar Libration Effects*. The application of the libration corrections to the first intermediate calibration time series yields a second intermediate time series. This time series has the form:

$$\frac{S_2(t,\lambda,\alpha,\gamma,l_{sc},b_{sc},l_{sun},b_{sun})}{S_2(0,\lambda,\alpha,\gamma,l_{sc},b_{sc},l_{sun},b_{sun})} = \frac{S_1(t,\lambda,\alpha,\gamma)}{S_1(0,\lambda,\alpha,\gamma)} f_4(l_{sc},b_{sc},l_{sun},b_{sun}) \qquad (6)$$

where $S_2 \equiv$ second intermediate, libration-corrected integrated radiances. The second intermediate calibration time series is shown in the figure *Lunar Calibration Time Series with Libration Corrections*.

6. Noise Reduction Correction

The second intermediate lunar calibration time series shows a noise that is correlated across all eight bands. This noise is a systematic error in the observations, common to all of the bands, whose primary source is the uncertainty in the determination of the y-size of the Moon used in computing the oversampling correction. An estimate of the correlated noise for each band can used to compute a noise reduction correction for the libration-corrected calibration time series. The correction has the form:

$$f_5(t,\lambda) = 1 - \frac{\frac{S_2(t,\lambda,\alpha,\gamma,l_{sc},b_{sc},l_{sun},b_{sun})}{S_2(0,\lambda,\alpha,\gamma,l_{sc},b_{sc},l_{sun},b_{sun})} - C(t,\lambda)}{C(t,\lambda)} \qquad (7)$$

where $C(t,\lambda) \equiv$ exponential fit to the second intermediate time series. The computation of the noise reduction correction is discussed in the document *SeaWiFS Noise Reduction Correction*. The noise reduction correction computed from the mean of the noise residuals for bands 4 and 5, which will be applied to all eight bands, is shown in figure *Noise Reduction Correction*. The second intermediate calibration time series with the noise reduction correction applied are shown in the figures *Corrected Lunar Calibration Time Series*.

7. Lunar Calibration Time Series

The fully-corrected lunar calibration time series is the intermediate time series with the libration corrections and the noise reduction corrections applied. The resulting time series has the form:

$$\frac{S(t,\lambda,\alpha,\gamma,l_{sc},b_{sc},l_{sun},b_{sun})}{S(0,\lambda,\alpha,\gamma,l_{sc},b_{sc},l_{sun},b_{sun})} = \frac{S_2(t,\lambda,\alpha,\gamma,l_{sc},b_{sc},l_{sun},b_{sun})}{S_2(0,\lambda,\alpha,\gamma,l_{sc},b_{sc},l_{sun},b_{sun})} f_5(t,\lambda) \qquad (8)$$

where $S \equiv$ corrected integrated radiances. As noted above, the corrected lunar calibration time series are shown in the figures *Corrected Lunar Calibration Time Series*. Examination of the figures shows that the periodic geometry effects and the systematic noise effects have been removed from the time series. The remaining scatter in the observations arises from random measurement error. The corrections for the changes in the radiometric response with time of the instrument are computed from the inverses of exponential fits to these time series.

The calibration time series for bands 1,2,and 5-8 are fit by two simultaneous exponential functions of time, while bands 3 and 4 are fit by single exponential functions of time. For the simultaneous exponentials, the time series are fit with a short period time constant of 200 days and with a long period time constant of 1600 days. For the single exponential, the time series are fit with the long period time constant.

Two different decay mechanisms are responsible for the changes in response of each of the bands. The first mechanism caused a rapid decrease in response that decayed away after approximately the first year of the mission. This effect is probably present in bands 3 and 4, though with a magnitude that is not detectable in the scatter of the observations. The second mechanism has been in effect over the entire mission. The long-period decay for the shorter wavelength bands (bands 1-4) most likely arises from yellowing of the instrument optics on orbit. The long-period decay for the longer wavelength bands (bands 5-8) most likely arises from charged-particle induced damage to the silicon photodiodes.